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Magnetically induced optical transparency of overdense plasmas due to ultrafast ionization

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Laser light can propagate through an overdense magnetized plasma as an extraordinary mode. The required stationary magnetic field may be supplied by ultrafast ionization of the medium [Phys. Rev. Lett. **61**, 337 (1988)]. The implications of this process on the interpretation of recent unexpected results [Phys. Rev. Lett. **79**, 3194 (1997)] in terms of extraordinary mode propagation, is briefly discussed. This physical mechanism opens new and exciting perspectives in high-intensity femtosecond interaction studies and related applications. [S1063-651X(98)50108-0]

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The possibility of light propagation through overdense plasmas was originally studied in the relativistic regime by Akhiezer and Polovin [1] and later applied to laser plasma interactions by Kaw and Dawson [2]. Since the development of multi-terawatt femtosecond lasers makes it possible to achieve a regime of laser-matter interaction never reached before, new interaction mechanisms are being proposed theoretically to model the interaction, including the anomalous skin effect [3,4], hole boring [5,6] and self-induced transparency [7,8]. These processes are also being extensively investigated experimentally worldwide [9–14].

To our knowledge, the propagation of electromagnetic waves in a magnetized plasma, in the so-called ''extraordinary mode,'' has not yet been taken into account as a candidate mechanism for ultrashort optical pulse propagation through overdense plasmas. In this paper we show that this kind of propagation can be efficiently activated with presently available ultrashort, intense laser pulses. The extraordinary-wave propagation also suggests a qualitative interpretation of unexpected results of a recent experiment [13]. It is well known that [15] the presence of a static magnetic field B_s perpendicular to the wave vector and parallel to the oscillating magnetic field of an electromagnetic (em) wave allows the wave to propagate, as an extraordinary wave, in a plasma whose density is above the critical density $n_c = {\omega_p}^2 m/4\pi e^2$. In this propagation mode, the oscillating electric field is orthogonal to the oscillating magnetic field and lies in the plane containing the wave vector, so that the mode is still perpendicular but partially transverse and partially longitudinal. Taking into account the dispersion relation for this mode, the plasma refractive index n is given by the following expression:

$$n^2 = 1 - \frac{n_e}{n_c}\,\frac{1-(n_e/n_c)}{1-(n_e/n_c)-(\Omega^2/\omega^2)}, \tag{1}$$

where n_e and ω are the electron density and the laser angular frequency, respectively, and $\Omega = eB_s/mc$ is the cyclotron frequency. Considering the characteristic frequencies ω_h (upper hybrid), ω_+ and ω_-,

$$\omega_h = \sqrt{{\omega_p}^2 + \Omega^2}, \quad \omega_\pm = \sqrt{{\omega_p}^2 + \frac{\Omega^2}{4}} \pm \frac{\Omega}{2}, \tag{2}$$

the propagation is allowed for waves of frequency $\omega > \omega_-$, excluding the forbidden frequency band $\omega_+ > \omega > \omega_h$. In terms of the electron density, this means that propagation is also possible at electron densities above n_c, provided $n_e < n_0(1+\Omega/\omega)$. Simple calculations show that, for visible light to propagate through highly overdense plasmas ($n_e \geqslant 10 n_c$), magnetic fields of the order of 10^9 G are necessary. This order of magnitude does not change substantially in the relativistic regime [16]. In the past, these high magnetic fields may have discouraged investigations on this particular mode of propagation for optical laser pulses. In addition, a suitable physical mechanism, capable of producing and maintaining a steady magnetic field parallel to the oscillating magnetic field of the wave, was still to be envisaged.

In the regime of ultrashort laser interactions, a mechanism for the generation of such a magnetic field has been identified and proposed by Wilks, Dawson, and Mori [11]. In fact, they have shown both analytically and via numerical simulations that, *provided the em field is already inside the medium*, an intense static magnetic field parallel to the oscillating magnetic field is generated as a consequence of the ultrafast ionization produced by an intense ultrashort pulse. In that paper, the authors focus on the up-shift of the laser frequency expected from the quick plasma creation. They predict two solutions for two counterpropagating waves, plus a stationary solution corresponding to a static magnetic field, which remains in the plasma long after the fast ionization. The magnetic field has the direction required to allow propagation of the extraordinary mode, and varies sinusoidally in space with the same wavelength of the em wave.

The analytical calculations, compared with computer simulations, show full agreement in the case in which plasma creation occurs in a single period of the wave. The order of magnitude of the static magnetic field is $B_s = {\omega_p}^2 E_0/({\omega_p}^2 + \omega^2)$, which can approach the amplitude of the oscillating field for $\omega_p \gg \omega$, i.e., for well-overdense plasmas. The theo-

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retical results of Ref. [17] were found to be consistent with the experimental observation and measurement of frequency up-shift of a microwave pulse in a rapidly growing plasma published later [18]. Therefore, the latter paper confirms experimentally the mechanism identified in Ref. [17], and indirectly supports the generation of a static magnetic field.

In the case of ultrashort laser pulse interactions, the creation of an intense time-independent magnetic field, parallel to the oscillating magnetic field, as predicted in [14], has important consequences on the propagation of the pulse itself, since it can enable overdense propagation as an extraordinary mode. To our knowledge, this paper focuses for the first time on the consequences that the predictions of Ref. [17] can have on the propagation of femtosecond pulses through dense matter and on consequent applications such as particle acceleration and laser fusion ignition. For this effect to take place, it is crucial that the medium be initially transparent to em waves, so that a plasma can be quickly created in the whole interaction volume. This volume ionization is the necessary condition to produce the discontinuity in time (in place of the discontinuity in space occurring when the light has to propagate in a vacuum-plasma interface) required for the onset of the magnetic field. Experimentally, this implies that the intense pulse has to propagate in the medium before ionizing it. In other words, the medium must be initially transparent and then must be ionized quickly, in a wave period or so. Considering that ultrashort pulses are normally affected by the presence of some sort of prepulse, an additional necessary condition is that no significant ionization is produced by the prepulse.

A possible experimental method suitable for studying this effect consists of the interaction of femtosecond high-contrast laser pulses with a thin foil of transparent material whose thickness is comparable to or smaller than the light wavelength. This method has many experimental advantages. As the effects of the prepulse are minimized [10], initial penetration of the leading edge of the short pulse is allowed, with the consequent possibility of volume ionization. Also, refractive effects on the propagating pulse are minimized, and direct measurements of transmittivity can be easily performed. On the other hand, the calculations of Ref. [17] do not apply rigorously to this case, since they have been obtained for a medium of length $L \gg \lambda$ (the light wavelength) to neglect the edge effect. This effect has to be included in the analysis of thin foil experiments. Second, once the ionization occurs at a given cycle in the leading edge of the pulse, the rest of the pulse experiences a discontinuity in space at the vacuum-plasma interface.

An experiment with very thin plastic foils ($L \approx \lambda/10$) was performed recently using 30-fs (about ten optical cycles) laser pulses [13]. The laser pulse was focused on a target with an angle of incidence of 20 degrees, and was linearly p-polarized. Surprisingly, considerable transmittivity was observed for the first time at intensities above 10^{17} W/cm^2, with almost complete transparency at an intensity of 3×10^{18} W/cm^2 [13]. Conditions for ultrafast volume ionization were fulfilled in that experiment, since it was tested that the prepulse did not produce substantial ionization. The spectra of the transmitted light were found to be blue-shifted for intensities close to the threshold of the effect, as expected from Ref. [11]. No shift was observable well above that threshold. This is not in contradiction with Ref. [17], because in this case the ionization is expected to involve only a small portion of the pulse energy, and the blue-shifted component would be out of the analyzed spectral region. Further, a perturbation on the transmitted pulse was observed in the near field after propagation, resulting in a beam cross section elongated in the direction parallel to the plane of incidence. This elongation could be due to diffraction from the spatial modulation of B_s in the same direction, as expected by Ref. [17].

The qualitative agreement between the observations described above and the expectations of Ref. [17], may suggest an interpretation of the high level of transmission observed [13] as being due to extraordinary-wave propagation in a self-generated magnetic field. If estimated from Ref. [17] (ignoring that in the experiment $L \ll \lambda$), at 3×10^{18} W/cm^2, 0.8 μm wavelength, B_s results are of the order of 10^8 G, which could allow propagation up to $n_e \approx 2n_c$. However, the electron density in the experiment of Ref. [13] was estimated to be much higher. This discrepancy implies that a more complex model based of ultrafast volume ionization is needed. In fact, one should take into account that $L \ll \lambda$, and the possible consequences: (i) the model of Ref. [17] For the generation of the magnetic field has to include the boundary effects; (ii) the spatial discontinuity faced by a part of the pulse at the foil boundary has to be included in the model; (iii) possible effects of the boundaries on the longitudinal component of the oscillating electric field, essential to the extraordinary wave propagation, must also be considered.

The latter point is particularly important, as the interference of the incident wave with the wave reflected by the second surface of the foil can decrease the amplitude of the longitudinal component of the electric field. This fact, in turn, reduces substantially the value of B_s required to allow propagation at a given n_e (with $n_e > n_c$). Simulations have been performed taking into account, inside the target, the interference effects of the forward-propagating laser radiation with that reflected at the plasma-vacuum interface [16]. These simulations show that, in the condition of the above-mentioned experiment, the longitudinal electron motion is strongly perturbed by even a small percentage of reflected radiation.

It is clear that this idea has to be further developed. In the meantime, a series of experimental tests can be performed in order to discriminate among the possible physical mechanisms likely to produce overdense transparency, and in particular to search for direct or indirect evidence of the occurrence of the quasistatic magnetic field. In this respect, one possibility would be to investigate possible diffraction effects on the pulse due to the spatial modulation of the magnetic field.

In conclusion, a possibility for the propagation of an intense femtosecond pulse through overdense plasmas has been introduced. The model is based on the well known extraordinary-wave propagation mode in a magnetized plasma, with the static magnetic field parallel to the oscillating magnetic field of the em wave. Such a static magnetic field can be created by the pulse itself if the conditions for ultrafast volume ionization are fulfilled, and can last for a time much longer than the ionization time. Experiments in femtosecond laser pulse interaction with thin dielectric foils are suitable for testing this effect, although their quantitative comparison with the model is not straightforward.

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